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Winter atmospheric circulation and river discharge in northwest Europe

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[1] More frequent western atmospheric circulation over Europe results in increased precipitation in winter, and could result in increasing river discharges. We made a quantitative assessment of the impact of variation in atmospheric circulation, defined by the frequency of western circulation in the Großwetterlagen classification system and the North Atlantic Oscillation (NAO) index, on variation in basin-average precipitation and winter discharges (December–February) of eleven large river basins that drain northwest Europe. Annual winter discharges amounts are highly correlated among these rivers (up to $r^2 = 0.82$, decreasing with increasing inter-basin distance), which may point to a common atmospheric forcing. The number of days of western atmospheric circulation in winter as indicated by the Großwetterlagen classification system is more closely related ($r^2 = 0.06$ to $r^2 = 0.28$, $p < 0.05$ or better) to winter river discharges than the NAO index. We therefore conclude that the frequency of western atmospheric circulation over Europe is a better indicator of climate variability and climate change impacts on river discharges in northwest Europe.
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1. Introduction

[2] Atmospheric circulation patterns are known to govern variation in precipitation across northwest Europe, particularly in winter [*Wibig*, 1999]. Some patterns of natural variation in atmospheric circulation have been recognized, of which the North Atlantic Oscillation (NAO) is probably best known. The NAO index is usually defined as the difference of normalized sea level pressures between the Azores and Iceland, and has been shown to correlate well with precipitation in parts of Europe, most importantly positively in Scandinavia and negatively in the Iberian peninsula [*Hurrell*, 1995]. Precipitation in locations in western and central Europe that are more distant from the coast, however, is only weakly correlated to the NAO index [*Hurrell*, 1995; *Hurrell and van Loon*, 1997; *Wibig*, 1999].

[3] Since it is widely recognized that precipitation strongly influences river discharges, research has looked for links between atmospheric circulation patterns and river discharges in Europe. *Peterson et al.* [2002] showed a positive correlation between the NAO index and discharge of northern Eurasian rivers. In a global analysis, *Dettinger and Diaz* [2000] found significant correlations between the NAO index and river discharge in many locations across Europe. *Shorthouse and Arnell* [1999], however, showed that strong relationships between the NAO index and winter river discharge in Europe can only be found in Scandinavia and the Iberian Peninsula. *Rimbu et al.* [2004] concluded that a highly smoothed NAO index and annual discharges of the central-eastern located Danube river basin correlate for only 35% of the time for the period 1856–1998.

[4] We made a quantitative assessment of the strength of the relationship between variation in atmospheric circulation and winter river discharges in northwest Europe (December–February). In particular, we address the question to what extent year-to-year variability in winter river discharges can be related to the NAO index. As an alternative we present relationships between river discharge and the frequency of western circulation as recorded in the so-called Großwetterlagen system [*Gerstengarbe et al.*, 1999]. This classification is based on the locations of high and low pressures and ridges and troughs at the 500 hPa level. Although the Großwetterlagen system has been considered a subjective classification scheme, it was found to perform equally well for daily precipitation, when compared to two other objective classification schemes [*Buishand and Brandsma*, 1997]. *Werner et al.* [2000] showed that the residence time of a particular type of western circulation of the Großwetterlagen system, the West cyclonic circulation, has increased since the 1970s, and some have related this increase to the occurrence of European river floods in the 1990s [*Caspary*, 1995].

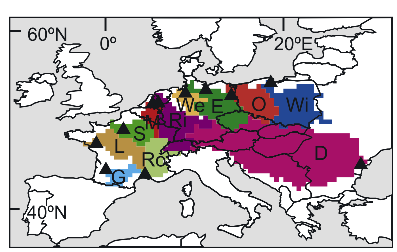

Figure 1. Location of the river basins in northwest Europe and the discharge gauging stations (triangles) shown on a 0.5 by 0.5 degree grid. Abbreviations are listed in Table 1.

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Table 1. River Discharge Gauging Stations[a]

River	Station	Lat.	Long.	Years	Gauged Area, km^2	Mean Winter Discharge, m^3 s^{-1} (% of Mean Annual Runoff)
Danube (D)	Ceatal Izmail, Romania	45.18°N	28.80°E	1921–1983	807,000	6028 (23%)
Elbe (E)	Neu-Darchau, Germany	53.38°N	11.47°E	1926–2003	131,927	798 (28%)
Garonne (G)	Mas d'Agenais, France	44.42°N	0.24°E	1920–1978[b]	52,000	912 (37%)
Loire (L)	Montjean, France	47.38°N	0.8°W	1863–1978[b]	110,000	1352 (40%)
Meuse (M)	Lith, Netherlands	51.81°N	5.45°E	1911–1983	29,000	555 (42%)
Oder (O)	Gozdowice, Poland	52.76°N	14.32°E	1900–1986	109,729	586 (27%)
Rhine (Ri)	Lobith, Netherlands	51.84°N	6.11°E	1901–2001	185,000	2619 (29%)
Rhone (Ro)	Beaucaire, France	43.92°N	4.67°E	1920–1978[b]	95,590	1919 (28%)
Seine (S)	Paris, France	48.83°N	2.25°E	1928–1978[b]	44,320	455 (42%)
Weser (We)	Intschede, Germany	52.96°N	9.13°E	1921–1983	37,790	442 (35%)
Wisla (Wi)	Tczew, Poland	54.09°N	18.80°E	1900–1986	194,376	964 (23%)

[a]See also Figure 1.
[b]Missing data in 1974 and 1975.

2. Methods and Data

[5] Data on monthly river discharges were taken from the RivDIS database at http://daac.ornl.gov/rivdis/STATIONS.HTM [*Vörösmarty et al.*, 1998] for nine northwest European rivers (Table 1 and Figure 1). Discharge data for the Elbe were collected from the Arbeitsgemeinschaft für die Reinhaltung der Elbe (ARGE) for the period 1926–2003, and for the Rhine from WaterBase (http://www.waterbase.nl) for the period 1901–2001. In addition, winter precipitation data (December–February) for the period 1901–1999 were collected from the CRU TS 2.0 data set, which contains 0.5 by 0.5 degree gridded monthly data based on observations [*Mitchell and Jones*, 2005]. Monthly precipitation was averaged over each river basin using the basin outlines shown in Figure 1. Basin outlines were taken from *Fekete et al.* [1999]. The NAO index over December–February for the period 1865–2003 was used as developed by *Hurrell* [1995]. This index is calculated as the difference of normalized sea level pressures between Ponta Delgada in the Azores and Stykkisholmur/Reykjavik in Iceland. The frequency of western circulation (FWC) in winter (December–February) was taken from the Großwetterlagen system for the period 1881–1997 [*Gerstengarbe et al.*, 1999].

[6] First, correlations were made between winter river discharges of different rivers, and a principal component analysis was performed. Secondly, correlations were made between basin-average precipitation and both FWC and the NAO index. Thirdly, regressions were made between winter discharges and precipitation per river basin. Finally, regressions were made between the two indicators of western atmospheric circulation, the FWC and the NAO index, and annual winter discharges.

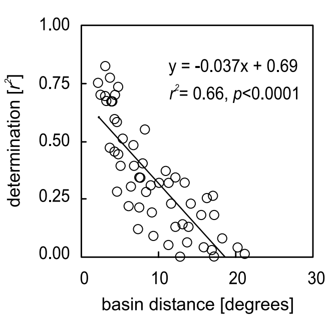

Figure 2. Relationship between coefficients of determination of winter discharges among European rivers and the distance between the geographical centers of the basins.

3. Results

[7] The winter discharges of the river basins in northwest Europe are highly correlated among each other (Table 2). This indicates that drainage systems across northwest Europe behave in a similar manner and may well share a common atmospheric forcing. The correlation is weakest between the rivers located in southwestern Europe (Garonne, Loire) and those in central Europe (Oder, Wisla). Correlation between discharges is probably governed simply by spatial proximity, as correlations are highest among adjacent basins (Figure 2).

[8] Precipitation was found to be important in determining the winter discharge in most river basins (Table 3). Variability in precipitation governed 50% or more of the variation in winter discharge in five out of the eleven basins, and correlations were significant in nine.

[9] Winter values of both the NAO index and FWC show great interannual variation (Figure 3). There is no strong relationship between the NAO index and FWC: the 5-year moving averages of the NAO index and FWC were only weakly correlated, though significantly (r^2 = 0.05, p < 0.01). Total basin-average winter precipitation was significantly correlated to FWC for nine out of the eleven basins. This basin-average precipitation was not significantly correlated to the NAO index (Table 3).

[10] The winter discharge of nine of the eleven rivers that were studied was significantly correlated to FWC (Table 4). The strongest relationships between FWC and discharge

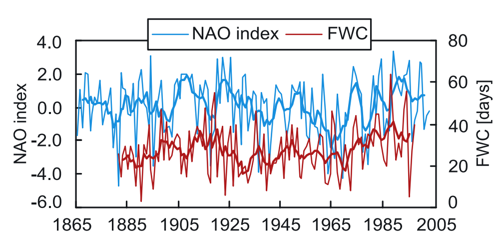

Figure 3. Time series and 5-year moving averages of the NAO index (1865–2003) and the frequency of western atmospheric circulation (FWC, 1881–1997) in winter.

Table 2. Coefficients of Determination (r^2) of Linear Regressions Among Winter River Discharges[a]

River	Danube	Elbe	Garonne	Loire	Meuse	Oder	Rhine	Rhone	Seine	Weser
Danube	–									
Elbe	0.34[b]	–								
Garonne	0.18[b]	0.06	–							
Loire	0.26[b]	0.13[c]	0.67[b]	–						
Meuse	0.23[b]	0.40[b]	0.21[b]	0.44[b]	–					
Oder	0.30[b]	0.77[b]	0.00	0.04[c]	0.23[b]	–				
Rhine	0.37[b]	0.51[b]	0.28[b]	0.48[b]	0.82[b]	0.31[b]	–			
Rhone	0.14[d]	0.09[c]	0.59[b]	0.67[b]	0.28[b]	0.00	0.45[b]	–		
Seine	0.18[d]	0.32[b]	0.39[b]	0.75[b]	0.70[b]	0.13[c]	0.73[b]	0.47[b]	–	
Weser	0.22[b]	0.67[b]	0.05	0.19[b]	0.70[b]	0.34[b]	0.69[b]	0.12[b]	0.39[b]	–
Wisla	0.32[b]	0.55[b]	0.01	0.04	0.25[b]	0.58[b]	0.32[b]	0.03	0.08[c]	0.34[b]

[a]Length of time series varies according to data availability, see Table 1.
[b]$p < 0.001$.
[c]$p < 0.05$.
[d]$p < 0.01$.

exist for rivers that are strongly correlated to precipitation and drain northwest parts of Europe (Elbe, Meuse, Rhine, Rhone and Weser). Basins that are located more to the south (Garonne, Loire) or to the east (Danube, Oder) have weaker relationships. Year-to-year variability in winter discharge of northwest Europe was not correlated to the winter NAO index (Table 4). Correlations between both winter (December–February) FWC and the NAO index and discharges in December-May do not produce better results, and lagged correlations between both winter (December–February) FWC and the NAO index and discharges in spring (March–May) give even weaker correlations (data not shown here).

[11] A principal component analysis on all rivers for a common period of 1928–1973 shows that the first and second principal components explain 80% of the variance in winter river discharges. In a stepwise multiple linear regression the first principal component was significantly correlated with FWC ($r^2 = 0.15$, $p < 0.01$) but not with the NAO index. The second principal component was again correlated significantly with FWC ($r^2 = 0.10$, $p < 0.05$) and not with the NAO index.

4. Conclusions

[12] Although significant links between the NAO index and river discharges have been found in the south and north of Europe [*Shorthouse and Arnell*, 1999; *Dettinger and Diaz*, 2000; *Peterson et al.*, 2002], our analysis of unsmoothed time series suggests that the correlation between year-to-year winter river discharges and the NAO index in northwest Europe is neither strong, nor significant (Table 4). The frequency of western atmospheric circulation (FWC) as indicated by the Großwetterlagen system appears to be a better indicator for the inter-annual climate variability on river discharges in northwest Europe.

[13] Recent research on North Atlantic climate variability has shown teleconnections with tropical sea surface temperatures [*Hurrell et al.*, 2004]. But smoothed time series of discharges of the Danube River, for instance, are only weakly related to tropical sea surface temperatures [*Rimbu et al.*, 2002, 2004].

[14] The FWC gives a better approximation of variability of river discharges in northwest Europe, as FWC in this system explains 6–28% of annual variation in winter river discharges. Still, this 28% cannot be considered sufficient for prediction purposes and other indicators may need to be included to increase the proportion of explained variance. We conclude that long-term interannual variability in discharge of northwest European rivers

Table 3. Coefficients of Determination (r^2) of Linear Regressions Between Basin-Average Precipitation and Frequency of Western Atmospheric Circulation (FWC, 97 Years), and the NAO Index (99 Years) in Winter

River	FWC, r^2	NAO Index, r^2
Danube	0.00	0.00
Elbe	0.27[a]	0.00
Garonne	0.01	0.00
Loire	0.15[a]	0.00
Meuse	0.41[a]	0.00
Oder	0.19[a]	0.02
Rhine	0.34[a]	0.00
Rhone	0.08[b]	0.00
Seine	0.34[a]	0.00
Weser	0.39[a]	0.00
Wisla	0.09[b]	0.00

[a]$p < 0.001$.
[b]$p < 0.01$.

Table 4. Coefficients of Determination (r^2) of Linear Regressions Between River Discharges and Precipitation, Frequency of Western Atmospheric Circulation (FWC) and the NAO Index in Winter[a]

	Precipitation		FWC		NAO Index	
River	r^2	Years	r^2	Years	r^2	Years
Danube[b]	0.23[c]	63	0.03	63	0.00	63
Elbe	0.34[c]	74	0.12[d]	72	0.00	78
Garonne	0.64[c]	57	0.09[e]	57	0.01	57
Loire	0.52[c]	76	0.06[e]	96	0.01	112
Meuse	0.60[c]	73	0.28[c]	73	0.01	73
Oder	0.31[c]	86	0.06[e]	87	0.02	87
Rhine	0.61[c]	99	0.27[c]	97	0.00	101
Rhone	0.65[c]	57	0.17[c]	57	0.00	57
Seine	0.37[c]	49	0.07	49	0.00	49
Weser	0.49[c]	63	0.23[c]	63	0.02	63
Wisla	0.11[d]	86	0.17[c]	87	0.00	87

[a]Length of time series varies according to data availability, see Table 1.
[b]21-year averaging for the Danube as performed by *Rimbu et al.* [2004] leads to coefficients of determination of 0.10,[e] 0.29,[c] and 0.61,[c] respectively.
[c]$p < 0.001$.
[d]$p < 0.01$.
[e]$p < 0.05$.

covaries significantly with North Atlantic climate variability and is much closer linked to the duration of westerly circulation than to large scale north-south pressure differences indicated by the NAO index.

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